Data Quality Control for Vessel Mounted Acoustic Doppler Current Profiler. Application for the Western Mediterranean Sea.

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SUMMARY: A systematic Data Quality Checking Protocol for Vessel Mounted Acoustic Doppler Current Profiler observations is proposed. Previous-to- acquisition conditions are considered along with simultaneous ones. Independently of internal systems, location and misalignment, the auxiliary systems to acquisition determine the accuracy range of the current velocity profiles. Simultaneous-to-acquisition navigation conditions provide the physically descriptive weight (or reliability) of significance for each individual current profile. The formulation of the Data Quality Checking Protocol is followed by actual applications and examples from cruises aboard R/V 'Garcia del Cid' in the Western Mediterranean Sea.

Key words: ADCP, GPS, Horizontal currents determination, Data reliability, Western Mediterranean

RESUMEN: CONTROL DE CALIDAD DE DATOS OBTENIDOS CON UN PERFILADOR ACÚSTICO POR EFECTO DOPPLER. Se propone un protocolo sistemático para el control de calidad de 10S dates obtenidos con un perfilador acústico por efecto Doppler (ADCP) instalado en un buque. Se consideran las circunstancias previas a la adquisición y las simultáneas a la misma. Independientemente de las condiciones técnicas, de localización del instrument y de su posible desalineamiento, 10S sistemas auxiliaries a la adquisición determinant el rango de precisión de 10S perfiles de velocidad de la corriente. Las circunstancias de navegación simultáneas a la adquisición permiten determinar y atribuir un grado de significación (o fiabilidad) a cada uno de 10S perfiles individuals. La formulación del protocolo de control de calidad de 10S dates se complements con su aplicación a una campaña realizada en otoño de 1992 a bordo del buque oceanográfico "Garcia del Cid" en el Mediterráneo occidental.

Palabras claw ADCP, GPS, Determinación de corrientes horizontals, Fiabilidad de dates, Mediterráneo occidental

INTRODUCTION

The Vessel Mounted Acoustic Doppler Current Profiler (VM ADCP) has become a standard instrument during the last decade aboard most research ships worldwide. An assessment of the reliability of the ADCP profiles is considered to be crucial for both having a clear quantitative physical description of the current velocity field and to integrate the ADCP records with further quantitative analysis with a known reliability (or weight) field. Up to now the accuracy of ADCP observations has usually been evaluated by different authors following four generic paths:

- Comparisons with current measurements recorded by other oceanographic instruments. This is the most common path. Several successful comparisons between observations by ADCP and eulerian current meters (Kosro, 1985; Castellón *et al.*, 1990; García et al, 1992) have been performed. Kosro (1985) found that observations located less than 1 km apart were highly correlated. The average difference over several weeks of data was less than 0.5 cm/sin comparison with moored ADCP.
- ADCP internal technical verifications (Chereskin et al, 1989; Chereskin and Harding, 1993) used together with instrument misalignment checking (Joyce 1989; Pollard and Read, 1989).
- Precision checking of ADCP auxiliary systems, generally the positioning (or navigation) system (Firing, 1991) and the ship gyrocompass (Griffiths, 1994).
- Comparison with laboratory simulations and numerical models of ADCP performance (Chereskin et al, 1989; Lien *et al.*, 1994; Chereskin and Harding, 1993).

The objective of this study is to merge some of these paths with other acquisition criteria to assess the reliability of each ADCP current profile. Neither direct comparisons with data by other in-situ oceanographic instruments nor laboratory/model ADCP simulations will be treated here. The proper technical operation of the ADCP acquisition system and its auxiliary systems will determine and condition the reliability of the ADCP profiles in an early stage, but the effect of other sources of error should also be considered. We will develop a systematic VM ADCP Data Quality Checking Protocol (DQCP hereafter) in the next section.

Applications and actual examples of each step of the DQCP, mainly from a cruise aboard R/V 'Garcia del Cid' in the Alboran Sea (Western Mediterranean) in Autumn 1992, are presented to illustrate the protocol.

VM ADCP DATA QUALITY CHECKING PROTOCOL DESIGN: DQCP

Our experience on ADCP data acquisition and its post-acquisition processing lead us to identify the conditions that affect the reliability of the ADCP profiles (García-Górriz, 1995). This has guided the design of the DQCP in sequential steps chronologically related to actual acquisition:

1) Controls Prior to Data Acquisition

1.1) Location

An inadequate location of the transducer frame can ruin the VM ADCP observations since turbulence generated by the ship motion may degrade the acoustic signal to a large degree. Likewise, an appropriate location should avoid interference with other onboard acoustic devices, especially if the latter operate with the same frequency or its harmonics.

1.2) Misalignment

The measured current velocity field relative to the vessel needs to be corrected by the ship motion to obtain the absolute water velocity. Such correction consists in a translation and a rotation. The translation can be estimated from navigational systems or via very accurate ADCP Bottom-Tracking operation (J3T hereafter) if available. The rotation arises because the transducers are usually aligned fore-aft, port-starboard in the so called Janus configuration, but they can be mounted with a different alignment specification. The orientation of the ship fore relative to true North is needed to project the relative velocity components into geographic ones. Any misalignment angle is known from installation and corroborated through calibration, because if not spurious current velocities will appear.

Most ADCP users rely on the routine calibration established by Joyce (1989). Two independent parameters are determined by this calibration: the misalignment angle a (horizontal), and the sensibility/scaling factor β, which is related with errors in the speed due to a vertical misalignment. Both are associated with misinstallation, and their temporal variabilit y is related to the malfunctioning of the ship gyrocompass. The detected Doppler velocity has to be rotated by *a,* scaled up by $1+\beta$, and added to the ship velocity to obtain the true water velocity. Two different calibration procedures are described by Joyce (1989):

1.2.1) Water- Tracking calibration **(WTC)**

Water- Tracking calibration is based on measurements of the ocean current velocities at different depths, and assumes that they are made in a single and homogeneous volume of water with steady current. By steaming over this volume from different directions, the same velocity values should be retrieved, within a noise error. A statistical analysis of the actual measurements enables estimation of a and β.

1.2.2) Bottom- Tracking calibration **(BTC)**

The Bottom- Tracking calibration is based on the comparison of the ship motion by simultaneous BT and GPS data. For **VM150**, if the sea bottom-depth is shallower than 400 m, the **ADCP** measures the velocity of a **backscattering surface** with no movement, the sea floor, through the BT. Since the BT ship speed is very accurate and the current is not involved in the calculation, the a, β estimations are **expected** to be more reliable and precise than **WTC** ones.

1.3) internal Systems

It is necessary to verify each device involved in ADCP acquisition: the acoustic signal processing unit, the transducers, and the operational acquisition computer, which should be carefully synchronized to the navigation system clock. Nevertheless, every observation is affected by instrumental errors, which introduce a **bias** error, as well as random errors.

The inaccuracy of a single **ADCP** ping is too large to **produce** a physically reliable observation. For this reason observations are internally averaged by the instrument to reduce the random error, which ranges from a few cm S-l to, in exceptional cases, tens of cm s-' **(RDI**, 1990). The magnitude of this random error depends upon several factors: **ADCP** emission frequency **(F** in Hz in equation (l)), vertical thickness of the water cell **(D** in m), number of averaged pings (N), and geometry of the acoustic beams **(Theriault**, 1986). For the instrument used here, and in other standard vessel-mounted **ADCPs** with 30° oriented transducers, the random error σ of the horizontal components of current velocity is computed by:

$$\sigma \text{ (m/s)} = 1.6\text{x } 105 \text{ /(F } D\, N^{1/2}) \quad \textbf{(Theriault}, 1986) \qquad (1)$$

The **bias** error depends as well on several factors: temperature, mean current velocity, signal/noise ratio, and **frequential** filtering configuration during internal processing of Doppler shift. **Chereskin** *et a/.* (1989) performed numerical simulations to evaluate this error. Lien *et al.* (1994) **combined** numerical simulations with comparisons of actual **ADCP** data. Bias error is estimated to be about 1 cm s^{-1}.

1.4) Auxiliary Systems

1.4.1) Navigational positioning : Global Positioning **System (GPS)**

The navigation positioning system is needed to calculate the absolute current velocity if either the ship has non-zero speed relative to the earth or BT ship data are not available.

Our vessels in 1992 used the conventional Global Positioning System (GPS). The main limitation of conventional GPS has been the deliberate degradation by the U.S. Defense Department (because of the Selective Availability policy for civilian users), in which a position has a 95% confidence interval of 40 m of radius. This precision can be temporarily higher (Firing, 1991). At present, differential GPS systems drastically reduce the positioning radius, and three-dimensional GPS gives precise estimates of ship heading, pitch, and roll (King and Cooper, 1993). These allow a very significant improvement in the accuracy of the absolute ADCP velocity profiles.

Independently of the particular navigational system used, an assessment of the maximum error associated with positioning is fundamental when no BT is available. Positioning information is the only way to compute the ship velocity (which is an order of magnitude greater than the current we want to determine). and will be the main source of imprecision in our measurements (pierce *et al.*, 1988, García-Górriz, 1995).

A previous limitation to the navigation system (independent of its provoked degradation) is the truncation of the values which reach the acquisition computer. This effect also has to be examined. And, of course, a systematic detection and smoothing of erroneous GPS values (jumps, peaks in position) is a mandatory preliminary step.

1.4.2) Ship Gyro: heading, pitch and roll

The gyrocompass measures the horizontal orientation or course of the ship and, when no 3D GPS is available, it is the only onboard device providing the ADCP system with the information about the fore-aft azimuth (with respect to the magnetic North). In addition to technical verifications, the gyro should also be adjusted to the actual cruise latitude and longitude (Griffiths, 1994). A small heading error produces as well a spurious velocity component perpendicular to the ship steaming.

The transfer of information between gyro and ADCP can be achieved through different interfaces. Most ADCPs use the Synchro device, which allows the reception of headings synchronized with acquisition, The nominal accuracy of Synchro devices is between 0.1 to 0.2° (King and Cooper, 1993), but periodic calibrations are needed since a Synchro- induced error may drift the gyro values to 10 over intervals from several days to a month (Firing, 1991). Drifts in the gyro between 0.5-2° are also possible (Griffiths, personal communication). Sudden turns of the ship cause an additional potential error in the gyro values: such turns excite persistent Schuler oscillations (Pollard and Read, 1989) and can produce a drift error of up to several degrees. These oscillations are generally reported to have periods between 20 and 80 minutes and are damp within a variable interval of time. Interestingly, the temporal evolution of the misalignment parameters is correlated with the presence of such oscillations. These are identified as the chief reason of variability in the gyro.

Some ADCPs include pitch and roll sensors. The ADCP employed in our cruises was not provided with *them.* Nevertheless, several studies conclude that the horizontal velocities corrected by such effect differ only by 1 cm s^{-1} from non-corrected (Kosro, 1985). Thus, we can neglect the pitch and roll induced error in our analysis as its order is the same as the bias error.

2) Controls Simultaneous to Data Acquisition

2.1) Navigation

Independently of technical conditions, optimal acquisition is achieved when the steaming motion of the ship is rectilinear and uniform during each profile sampling. The ship course should be as constant as possible to minimize the effects of both gyro and synchro variability over the observations. The ship speed should also be as steady as possible. If variations occur over the acquisition interval, the absolute current velocity will have reduced reliability, as only an average of the ship motion is removed, not the actual motion. The DQCP pays special attention to these variations as they significantly reduce the reliability.

A set of ship speeds and courses describe the ship motion during the acquisition averaging interval for each current profile. Over that set, standard deviations (std) are calculated for both variables so each profile will have an estimator of the variation of the ship speed and course, that can be used to immediately detect accelerations, decelerations, or turns, and consequently to identify non-reliable profiles which should be discarded.

We establish the reliability threshold by analyzing the GPS data of profiles recorded under optimal conditions (straight trajectory with constant ship speed), which we will call 'navigation profiles' to distinguish from 'station profiles' squired during CTD casts. Histograms of the estimators should show normal distributions, and we use this to define the threshold: reliable profiles will be those laying within an interval of a specific number of std from the gaussian maximum. The threshold will be cruise-dependent, and the chosen number of std will depend on further current profile applications

2.2) Acoustic signal intensity

Assuming optimal navigation conditions, if the echo intensity from a water cell at a given depth is very low, the signal/noise ratio will also be low and consequently the observation reliability. Causes for low intensity echo from a water cell are diverse: the distance between the cell and the receptor and/or the sparse presence of passive backscatterers within that water cell. These acoustic circumstances are assessed by the ADCP system through the Percent-Good variable, or percent of the acoustical signal 'heard' by the system during the acquisition interval (echoes with signal-to-noise ratio higher than 6 dB). Measurements with a low Percent-Good do not guarantee that the associated echoes have enough energy to resolve the Doppler shift. An automatic verification is performed for each cell in the post-acquisition checking for every depth and profile. A threshold is imposed and out of range measurements are dismissed. The usual threshold is 90% (Munchow *et* al., 1992, Candela *et al.*, 1992).

2.3) Homogeneity of the water cell

The homogeneity of the water cell is one of the principal hypothesis assumed in ADCP data acquisition. It is needed as observations are averaged both horizontally and vertically for every water cell. Assuming a VM ADCP with the Janus configuration, each horizontal velocity component is estimated together with two estimates of the vertical component. The order of magnitude of the vertical velocities in the ocean is generally about three orders of magnitude smaller than horizontal velocities, with the exception of specific regions such as where deep water formation occurs (Schott and Leaman, 1991). Although VM ADCP accuracy is not enough to give reliable vertical velocity values, the difference bet ween the two estimates, also called 'error velocity', allows us to evaluate the assumption of horizontal homogeneity y over the examined water volume (RDI, 1990) From our own experience, persistent high error velocity values may also be a symptom of acquisition system malfunction. Analogously in the acoustic conditions, an automatic verification is performed in post-acquisition by considering a threshold value. The threshold value depends on the variability of the study area. In this fashion, cruises in the Atlantic ocean use a threshold of 20 cm s^{-1} (Munchow *et al.*, 1995). .

3) Other error sources

3.1) Air bubbles in front of the transducer head

All acoustical equipment operating into the sea can be affected by the presence of air bubbles. The latter can significantly degrade the data quality as they may produce high spurious current velocities over the shallower water cells and in the direction of the ship motion. Leaman *et al.* (1989) describe actual examples. This is often solved by placing the transducer frame deeper in respect to the ship keel. New (1992) empirically modeled the effects of the presence of air bubbles on the observation quality and parameterized the most relevant factors in their production: sea state, wind, and ship speed and course.

3.2) Bias error due to the presence of organisms with non-passive movement

The ADCP actually measures the movement of backscatterers in the sea, not the movement of the water itself. Therefore. accurate observations of the current velocity require that these backscatterers effectively either move passively within a water cell or swim randomly. Their movement relative to the current should have a zero mean over the acquisition interval. Several authors have observed that the assumption of passive movement/random swim is occasionally not fulfilled (Frietag et al, 1992). This is the case of daily vertical migrations of zooplankton, which may affect the estimates of horizontal velocities and produce bias errors at the depths implicated in the migrations (Wilson and Firing, 1992). As well, organisms with non-passive horizontal movement maybe present in the backscattering cell and produce bias errors in the same fashion as they degrade the acoustical signal and lead to an underestimate of the current velocity. These cases were detected on moored ADCP data, which seemed to attract such organisms (Frietag et al, 1992).

APPLICATION FOR THE WESTERN MEDITERRANEAN

The R/V “Garcia del Cid”, owned by the Spanish Council for Scientific Research (CSIC), was the first Spanish oceanographic vessel to operate an ADCP in 1989. On September-October 1992, an oceanographic cruise (*FE92*) took place in the Alboran Sea (Sánchez, 1992; Viúdez *et al.*, 1996), in the frame of the first phase of the European Union MAST program Mediterranean Targeted Project. In a preliminary leg to this cruise, a calibration experiment was performed during 10 h on 19 September. The DQCP described in the previous section was applied to the ADCP measurements recorded during this cruise, and especially to the calibration leg.

1) Cent rots Prior to Data Acquisition

1.1) Location

A RD Instruments VM150 ADCP was installed in February 1989 in the “Garcia del Cid” under the supervision of the manufacturer. The chosen placement, in the central third of the hull length, was supposed to be favorable since it was away from any turbulence generated by the bow during steaming. In fact, the first measurements, in the area of the along slope current off Barcelona, showed a velocity field fully coherent with previous knowledge (Castellón et *al.*, 1990), in spite of having been recorded without any detailed control as the one deseribed here.

On the contrary, the same model of ADCP was installed in 1991 aboard the Spanish R/V ‘Hesperides’ together with *other* acoustic sounders, not far from the bow due to the vessel design, The first data showed anomalously high vertical velocities along a water column of about 30 m below the heads of the transducers, and further careful tests also indicated contamination of the horizontal velocity dependent on the ship speed. After analyzing the problem the instrument was moved to a central location, and since then has produced excellent data sets (e.g. Allen *et al.*, 1996).

1.2) Misalignment

Due to the VM ADCP installation onboard the R/V ‘García del Cid’ the misalignment angle should be theoretically zero. This was checked during the calibration leg at the beginning of the 1992 cruise. this leg was specifically designed to fulfill repeated straight transects over a shallow zone, so all recorded profiles had ship speed and course by BT (fig. 1). These conditions enabled estimation of the misalignment angle and the scaling/sensibility factor by the two procedures described by Joyce (1989):

1.2.1) Water- Tracking calibration **(WTC)**

We calculated a ,β over the whole data set of the calibration leg, with 5 min averaged current profiles. Table 1 shows the parameters variation with depth. Both a and β tend to slightly grow with depth, but deeper cells are less significant since the acquisition was in a shallow area (only 65% of the total profiles reach 120 m). The representative mean for the misalignment *a is* 0.07° with 0.02° std. and for the scaling factor $1+\beta$ the result is 1.03, with 0.03 std.

1.2.2) Bottom- Tracking calibration **(BTC)**

The BTC parameters were computed using different profile averaging times (5 min. 30 min. 1 h and even original 10 s profiles), over the whole data set. All the results are very similar in both mean value and std. The mean values are in the range 0.038 to 0.040° for a and 0.015 to 0.016 for β. Given the uniformity. we used the parameter values from the original profiles a = 0.0396 ± 0.0246° and β = 0.0154 ± 0.0149. If the computation is made with the rest of the *FE92* BT profiles, the results are a = 0.026± 0.016° and β = 0.017* 0.009; the std is smaller but less significant since the number of BT profiles is much smaller than during the calibration leg.

The difference between BT ship speed and ship speed derived from GPS has been analyzed for two cases ('Table 2): (a) Profiles whose speed values fell between ± 1 std of the mean. This results 90.4% of files. (b) Only profiles whose speed was between ± 0.5 std of the mean, resulting in 86.0% of files. Before correcting BT ship speed for misalignment, its difference with GPS speed is about -8.2 for case (a) and -7.7 cm s^{-1} for case (b). After correcting for misalignment angle and sensibilit y factor (the speed is only affected by the latter), such differences decrease spectacularly 0.08 for the less restrictive case and 0.0001 cm s^{-1} for the more restrictive one. The std indicate that conventional GPS data which has been adequately averaged can provide an accurate estimate of the ship speed, with a range of error of about ± 7.7- 8.6 cm s^{-1}, which is totally consistent with the GPS intrinsic inaccuracy (subsection 1.4.1). As typical ship speeds are of the order of 500 cm s^{-1}, the error is about 1.5%.

Considering the mean value for a (0.040), the error induced by misalignment leads to a 0.07% spurious speed perpendicular to steaming, which means 0.35 cm s^{-1} for the ship speed and 0.035 cm s^{-1} for the current.

The mean scaling or sensibility factor $(1+\bar{\beta})$ is 1.016, and thus the measurements are underestimated in modulus by 1.6%. The ship speed will be underestimated by about 8 cm s^{-1} and the current velocities by 0.8 cm s^{-1}. For this specific VM ADCP installation, the scaling factor produces more error over the observations than the transducer misalignment.

The misalignment angle has higher values for WTC (0.07") than for BTC (0.040). For 13, the mean value is about 0.03 for WTC opposed to 0.02 for BTC. This discrepancy implies a difference of 1 % in the speed calculation, and other authors have also observed it (Pollard and Read, 1989). It is thought to be due to the different signal processing mode between WT and BT, since with BT mode a long ping is emitted, originating a narrower spectrum than in the WT mode. Therefore, BT mode allows a very accurate determination of the Doppler shift, Also, as mentioned above, the assumption of homogeneity of the several times crossed water volume is not always strictly fulfilled. Our experiment lasted 11 h, which is not very long but sufficient to have remarkable current variation due to different phenomena, as tides, for example. For BT mode, the current and its variation are not involved in the calculation, so this mode is considered to be less noisy than WT and to provide more accurate values for a and β.

The Joyce (1989) formulation allows the calculation of the error for *a* and β in BTC: Aa= ± 0.02', $\Delta\beta$= ± 0.01. The speed error of the steaming component is approximately ±3.5 cm s^{-1} and ±0.2 cm s^{-1} on the perpendicular one. We conclude that variability in a is mainly due to gyro instability and errors (Pollard and Read, 1989). For our ADCP, both *a* and its variability are small compared to course inaccuracy by conventional GPS positioning or the calculated heading biases. To study the possible temporal evolution of the calibration parameters, estimations of the parameters have been calculated over shorter running time intervals than that of the entire calibration leg. Fig. 2 summarizes this evolution when the calculation is made separately for each rectilinear transect (Fig. 2a,c) and for intervals of 30 min. using 5 min profiles (Fig. 2b,d). Profiles that correspond to changes of course have been previously eliminated. We will see that the oscillation patterns of *a* (Fig. 2b) correspond to gyro Schuler oscillations (see 1.4.2).

1.3) internal Systems

For the RDI VM150 ADCP onboard R/V 'Garcia del Cid', with 30" transducer configuration, the random error in horizontal velocity is calculated by equation (l). The configured values of F, D and N are: F= 153.6 kHz, D=8 m, N=5 x 60s / (10s each 4 pings, thus 2.5 s each WT ping). Therefore, the resulting random errors are:

σ = 1.2 cm S-l (if averaging over 5 min and 8 m)

σ = 1.7 cm s^{-1} (if averaging over 2.5 min and 8 m)

σ= 6.54 cm s^{-1} (if considering the previous ADCP raw profile averaging of 9.99s and 8 m)

For this cruise the averaging interval is 5 min and then the random error associated with ADCP observations is about the same order of the bias error (within the range 0.5- 1cm/s). The actual results of σ show that for longer averaging intervals, the bias error would be greater than the random one.

1.4) Auxiliary Systems

1.4.1) Navigation positioning: Global Positioning System (GPS)

The GPS positioning of the ship provides actual values of longitude and latitude, which are updated every several seconds (2s for our cruises). During this cruise, the acquisition computer clock showed no time drift and its synchronicit y with GPS was verified.

For the *FE92* calibration the ship steamed without interruption throughout, thus fulfilling the assumption of as constant as possible ship speed and course. Thus, the ship motion variability is attributed to both the inaccuracy of GPS positioning (which has implicit noise) and to navigation conditions (effect of winds and currents on ship motion and/or intrinsic random variations in navigation because of vibrations in the ship technology). In these cases, the GPS positioning inaccuracy value will be overestimated, which constitutes a meaningful result as it provides the error window range. The mean ship speed was 9.65 ± 0.57 kt (496.44 ± 29.32 cm s^{-1}) from direct BT estimation, or 504.38 cm s^{-1} after misalignment correction. The estimation from GPS gave 9.78 ± 0.61 kt (503.13 ± 31.38 cm s^{-1}), so both mean speeds have a difference of about 1 cm s^{-1}.

A first inspection of GPS positioning data indicate that 0.05% of them were totally erroneous, and thus dismissed (0.04% for the whole cruise), and 7% were affected by 'jumps' that required smoothing (6.6% for the whole cruise). The GPS data truncation effect corresponded to 0.01 geographical minutes. This means that two consecutive positioning (2s time difference) with the same latitude value, can actually be distant in a range of O- 17 m (as 0.005 and 0.014 are rounded to 0.01), and between O- 14 m for longitude. This truncation is relevant because it determines that no consecutive pair of GPS locations (longitude, latitude) can be used to calculate a likely ship movement, Over a 5 min acquisition interval, the truncation effect gives an uncertainty range of O- 7.3 cm s^{-1} for ship velocity.

A strategy to calculate simultaneous-to-5 rein-profile ship speed and course from GPS, and partially to avoid the truncation problem, consists in a running average over a 20 s window. Thus, a new collection of ship speed and course can be constructed every 2s and used to calculate the reliability estimators from GPS. These data have a 0-0.8 m location uncertainty because of truncation.

The std distribution of the GPS positioning (longitude and latitude) simultaneous to the 5 min interval current profiles has a normal shape. The values of the longitude and latitude mean variability in meters, are showed in line a):

	Var. longitude(m):	Var.latitude(m):
a)	18.88 ± 12.07	17.69 ± 13.44

b) *15.84 ± 7.73* *11.46 ± 6.79*

Line b) shows the results of a more restrictive calculation, which only considers the variations within a single std. Therefore, the mean variability in both latitude and longitude is about 18 m in case a) and 14 m in case b). These GPS overestimates lead to a speed inaccuracy of 6.5 -8.5 cm s^{-1} through equation $\delta v = r\sqrt{2}/\delta t$, where r is the uncertain y radius and δt the averaging time interval,

The correlation between ship speeds and courses from GPS and those from BT (corrected by the misalignment parameters) is 0.999902 and the std of their difference is 7 cm s^{-1} for 5 min intervals. Considering that BT estimations have a low associated instrumental error, this result is consistent with the range of speed inaccuracy of 6.5 -8.5 cm s^{-1}, calculated strictly from GPS data. Considering also that the usual GPS positioning inaccuracy has a typical 40 m radius (Firing, 1991), the speed inaccuracy over 5 min interval would be 19 cm s^{-1}, which is two times our result for the FE92 calibration.

The speed inaccuracy range of 6.5 -8.5 cm s^{-1} corresponds to a course inaccuracy of 0.7°- 1° for 5 min intervals. The inaccuracy produced by the three-dimensional GPS, which is 0.057° in real time (as design specifications, King and Cooper, 1993), is an order of magnitude lower.

1.4.2) **Ship Gyro: heading**

The comparison of the gyrocompass heading value that reaches the ADCP acquisition system, with the ship course from conventional GPS is very informative about the gyro performance, especially its temporal variability. The 5 min averaged angle of the ship bow (heading) and the angle of the ship trajectory with the North (effective course) are not *a priori the* same, since the steaming maybe conditioned by the drag of either current or wind. However, their high correlation makes comparison very useful.

During acquisition, the heading values reaching ADCP were constantly checked against direct simultaneous gyro data, to correct for any change of the offset, which is configured when the acquisition system is started and that can be affected by synchro failures.

Fig. 3 shows comparisons between 5 min averaged gyro heading and other variables which give information about the ship course. The heading HE has a mean difference of 4.4° and 3.3° std with the BT estimated course HEBT. Both HE and HEBT receive heading information from the ship gyro via synchro, although the corresponding WT and BT modes sample this information at different times as they constitute different pings.

The mean difference of HE with GPS computed course (named HGPS) is 6.6° and 3.6° std. HGPS is computed after applying a running-average of 20 s over the GPS positions, to minimize noise and truncation effects. HGPS and HEBT are two estimations of the same variable (the effective course over ground). but obtained using different navigation devices (GPS and gyro). There is a mean difference of 2.29° and 1.41° std between them, that should be caused by the gyro errors themselves plus GPS inaccuracy. Table 3 shows these results for the calibration leg and for the rest of the cruise, where the mean differences decreased but the std were higher.

The differences or residual courses in Fig. 3 seem to follow a quasi-sinusoidal pattern, which may obscure additional information. Such temporal evolution has been noted as well the determination of the misalignment parameters (1.2). The residual courses between HE and HGPS estimations have been fitted with two consecutive sinusoids with periods of Tl= 75 min and T2 = 110 min. The average amplitude for both is 7º, and the discontinuity point between both sinusoids coincides with the 90º turn at profile 58.

This situation corresponds to a ship gyro affected by Schuler oscillations, which in general have an amplitude of several degrees and a characteristic period between 20 and 84 min. These oscillations are excited by ship turns, are damped, and have a complex temporal evolution directly dependent on the specific ship gyro (King and Cooper, 1993). Damping is not evidenced in these records of the calibration leg, since the consecutive frequent turns (Fig. 1 a,b) did not allow its manifestation; however, it was detected later during the *FE92* cruise. A similar fit for the residual course between HE and HEBT is achieved by a double sinusoid with an average amplitude of 4º, and the same Tl and T2 periods, but not in the smaller residual between HEBT and HGPS.

Therefore, the reaction of the ship gyro to turns has been detected and identified. However, the cruise time gyro specifications are not available and its effect cannot be removed from the headings actually used by ADCP. To perform a rigorous correction, a longer gyro calibration concurrent with the cruise would be necessary.

2) Controls Simultaneous to Data Acquisition

2.1) Navigation

As explained in the DQCP formulation, std of course (sang in Fig. 4) and speed (svel) within a 5 min averaged profile are used as estimators of profile reliability. On Fig. 4 histograms for the two estimators are displayed for the FE92 cruise. For the calibration leg (data not shown), with no stations but turns, the std normal distributions are centered at 4-5 cm S-l and 4°. This value is much lower than for the whole cruise navigation profiles (13- 14 cm S-l), but for the ship course are quite similar. For station profiles, we obtain approximately 40 cm s^{-1} and 40-60°.

The reliability threshold can be defined by analyzing these histograms: calculating the mean and std of the estimators. For the calibration leg, profiles within one std of the mean estimator represent 86% of the total, and 90% within two std. 84% of FE92 navigation profiles lie within 1 std. but only a few of the station profiles were in that range. In stations, the vessel is moving and turning- dragged by winds and currents- even if the engine is off. Depending on the further use of the current profiles, a specific threshold must be chosen, It is clear that station profiles have to be discarded for most applications.

Once the non-reliable profiles are identified, we can display them in function of their mean speed (Fig. 5). Non-reliable courses correspond mainly to almost zero speed (station profiles: ship motion is very low but uncontrolled), while non-reliable speeds tend to be intermediate values between stop and full steaming, that is profiles recorded under acceleration or deceleration.

2.2) Acoustic signal intensity

Examining all the records with more than 10Y. of Percent- Good (hereafter PG), it is observed that PG decreases with depth, though it also happens locally for shallow cells, probably because of lack of backscatterers. Rough seas can be also a reason for a more rapid decrease of PG with depth. With the exception of unfavorable conditions, nearly 80% of total records for cells at all available depths are at least 90% of PG. For cells with depth shallower than 100 m, it is 95% of the total, We used 90% as the threshold for this DQCP application.

During *FE92* one of the ADCP transducers did not work, With only three transducers operative, horizontal components of velocity can be still independently calculated, plus one vertical velocity estimation. The ADCP system itself informs about the echo intensity received, and Fig. 6 clearly shows that transducer #2 was not working. After calibration and cleaning, the four transducers worked properly in another cruise (*Mphmed93*) in July 1993 as observed on Fig. 7. This is not the only acoustic difference between both cruises, perhaps due to the maintenance operation performed between them. In FE92 the three transducers do not “hear” the same average intensity, and appear to be partially ‘deaf for echoes between 120- 150 dB at depths shallower than 200 m, while deeper echoes seem to arrive correctly, perhaps due to the different characteristics of the sampled area.

2.3) **Homogeneity of the water cell**

Since only three transducers were operative, the error velocity was not available as reliability estimator for FE92. For an example of this step of the designed DQCP, we use *Mphmed93 cruise.* A mean error over each depth is plotted in Fig. 8a. The error velocity deeper than 170 m falls within the range -2 to O cm s^{-1} . For shallower cells, the range is wider. -4 to 1 cm s“^l, due to the higher inhomogeneit y of the profiled water volume. This result will directly depend on the study area. For this cruise profiles are basically located at coastal areas along the NW Mediterranean between 40° N off the Spanish coast and 42”N off the Italian coast.

Fig. 8b shows that less than 20% of the individual records are out of the range -5 to 5 cm s^{-1} . With a typical Atlantic threshold of 20 cm s-l, 98% of individual records would be acceptable. A threshold of 5 cm s^{-1} has been chosen here, but a different one could be defined depending on the further calculations to be done with the current measurements.

3) **Other sources of error**

No information is available, but we assume that clouds of bubbles and non-passive organisms can degrade the observations to an extent no larger than the one provoked by conventional GPS positioning or the ship gyro.

4. CONCLUSIONS

After analyzing the different sources of error that can influence the measurements with an ADCP onboard an oceanographic ship, a Data Quality Checking Protocol for Vessel Mounted ADCP has been proposed, The DQCP contemplates several consecutive checking phases:

First, controls prior to data acquisition should be done. These refer to the VM ADCP placement, the possible existence of misalignment, and assessment of random and bias errors of the instrument. Within this same category, we conclude that the verification of the auxiliary systems, that is navigation positioning and ship gyrocompass, is necessary to assess the derived accuracy of the current profiles. Within the control steps/conditions simultaneous to acquisition, the actual navigation is the most important. From navigation we derive the quality or reliability estimators for each one of the recorded current profiles. A threshold of reliability may be imposed for each cruise and depending on the desired error requirements on further calculations. Navigation with turns and/or changes in speed degrades the quality of the ADCP current profiles. As velocity and course estimators have normal distributions, a number of std is to be selected as threshold. The acoustic signal intensity and the water volume homogeneity conditions are also considered in this group. Finally, other sporadic situations may affect the current profiles, as the presence of air bubbles or non- passive movement organisms.

The formulation of the DQCP was designed *to be* as general as possible, and other navigation systems could be taken into account for future cruises. In fact, the use of the new differential and 3D GPS systems in combination with VM ADCP provides very precise navigation and heading (see e.g. Allen *et al.*, 1997). The immediate consequences are an improvement in the accuracy of the current profiles and the avoidance of the errors induced by gyrocompass Schuler oscillations.

From the application of the DQCP to cruise FE92 on the Western Mediterranean the accuracy of our cruise current profiles has been determined. Thus, assuming an internal bias error of 1 cm s^{-1}, the random error for 5 min profiling time is 6.5 cm s^{-1}. The conventional GPS implies, again for a 5 min interval, a velocity inaccuracy in the range of 6.5 -8.5 cm S-* and a course inaccuracy of 0.7 - 10. The presence of spurious Schuler oscillations in the ship gyrocompass can be detected and avoided for future cruises. The misalignment parameters are found to be relatively small, although the scaling factor has a higher importance over the current profiles than the actual misalignment angle. Also, BT ship speeds corrected for misalignment show a difference of hundredths of cm s^{-1} with GPS simultaneous ones, and with a std of about 8.5 cm S-l, which still is within the velocity inaccuracy range by GPS estimates. The temporal variability of the misalignment angle also shows the effects of Schuler oscillations in the gyrocompass functioning.

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Table 1 Calibration leg: Depth variation of Water Tracking Calibration parameters a ,β.

Depth(m)	$\bar{\alpha}$ (°)	$\bar{\beta}$
-16	0.0620 ± 0.0210	0.0299 ± 0.0091
-24	0.0660 ± 0.0207	0.0294 ± 0.0100
-32	0.0674 ± 0.0189	0.0293 ± 0.0106
-40	0.0675 ± 0.0179	0.0287 ± 0.0102
-48	0.0680 ± 0.0184	0.0274+ 0.0088
-56	0.0682 ± 0.0170	0.0338 ± 0.0111
-64	0.0679 ± 0.0177	0.0286 ± 0.0154
-72	0.0679 ± 0.0172	0.0265 ± 0.0068
-80	0.0684 ± 0.0170	0.0268 ± 0.0236
-88	0.0684 ± 0.0174	0.0272 ± 0.0249
-96	0.0689 ± 0.0157	0.0265 ± 0.0277
-104	0.0696 ± 0.0156	0.0274 ± 0.0282
-112	0.0704 ± 0.0171	0.0288 ± 0.0382
-120	0.0705 ± 0.0177	0.0278 ± 0.0382
-128	0.0712 ± 0.0181	0.0278 ± 0.0606
-136	0.0702 ± 0.0177	0.0304 ± 0.0337
-144	0.0700 ± 0.0182	0.0284 ± 0.0233
-152	0.0704 ± 0.0176	0.0300 ± 0.0232
-160	0.0706 ± 0.0183	0.0325 ± 0.0374
-168	0.0704 ± 0.0170	0.0309 ± 0.0465
-176	0.0700 ± 0.0173	0.0347 ± 0.0566
-184	0.0697 ± 0.0174	0.0355 ± 0.0567
-192	0.0699 ± 0.0168	0.0369 ± 0.0568
-200	0.0704 ± 0.0160	0.0383 ± 0.0606
	$\bar{\alpha}$ = 0.0689 °±0.020°	$\bar{\beta}$ = 0.0302± 0.034

Table 2 Comparison of BT and GPS ship speed for profiles with speed values within a) mean value± 1 std, b) mean value±0.5 std.

velbt: BT ship speed non-corrected for BTC parameters

cvelbt: BT ship speed corrected for BTC parameters

velgps: GPS ship speed.

	No a, β correction	a, β correction
%Data	velbt-velgps (cm s^{-1})	cvelbt-velgps (cm s^{-1})
a)90.4	-8.17458.550	0.0823 ±8.5651
b)86.0	-7.670 ±7.789	0.0001 ±7.6909

Table 3 Residual courses between the different estimators: HE gyro heading, HEBT bottom tracking course, HGPS GPS effective course

Cruise	(HE-HEBT)	(HE-HGPS)	(HEBT-HGPS)
Calibration	4.4° ± 3.3°	6.6° ± 3.6°	2.3° ± 1.4°
FE92	1.4° ± 4.6°	1.2° ± 4.3°	-O.1° ± 4.2°

Captions

Figure 1: *FE92* cruise in the Alboran Sea, September-October 1992: a) location of consecutive 1-hour-averaged ADCP profiles. b) 5 minutes-averaged profiles during the calibration leg.

Figure 2: Bottom Tracking mode computation of ADCP misalignment parameters using 5 rein-averaged profiles. Temporal variability:
a) Parameter **a** for each one of the 8 straight transects
b) Parameter a calculated for 30 min intervals
c) Parameter β for each one of the 8 straight transects
d) Parameter β calculated for 30 min intervals.

Figure 3: Angular residual differences in the calibration leg for each 5-rein consecutive ADCP profile of: a) ADCP gyro heading (he) and heading from BT (hebt). b) 'he' and effective course from conventional GPS (hgps). c) 'hebt' and 'hgps'. d) case b) fitted with sinusoids.

Figure 4: FE92 cruise occurrence histograms of: a) Course estimator 'sang' for navigation ADCP profiles. b) Same as a) but for station ADCP profiles. c) Speed estimator 'svel' for navigation ADCP profiles. d) Same as c) for station ADCP profiles. See text for definition of sang and svel

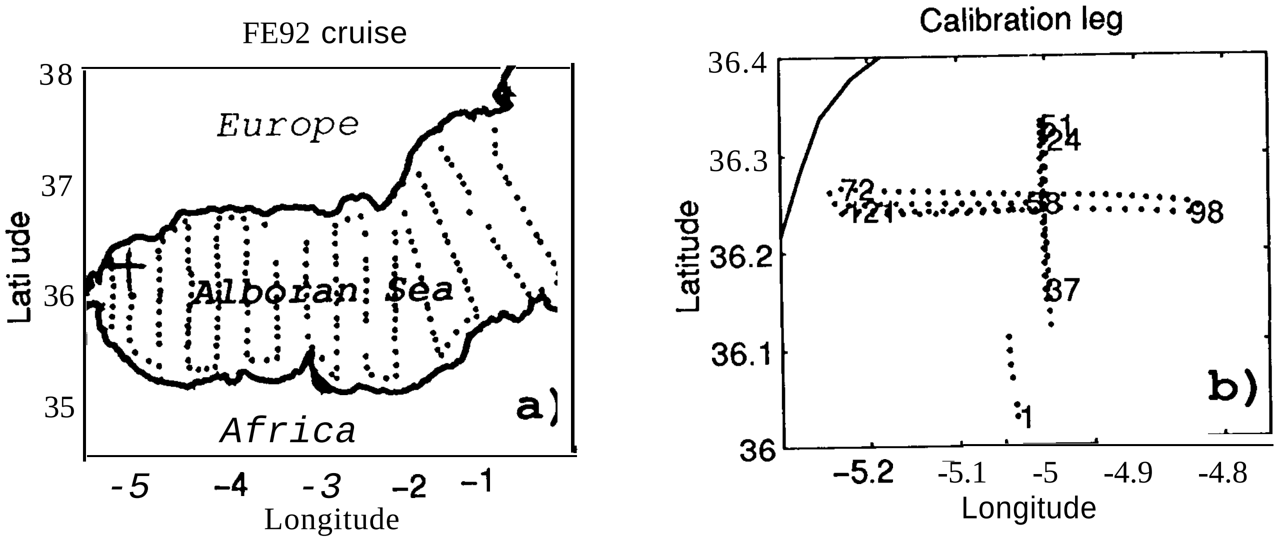
Figure 5: *FE92* profiles with non-reliable course (a), and non-reliable speed (b) in function of ship speed. Vertical scale is arbitrary.

Figure 6: a) to d) *FE92* echo intensity with depth for each ADCP transducer. e) Same but averaged for each transducer. f) Average of the four transducers.

Figure 7: Same as Fig. 6 but for *Mphmed93* cruise.

Figure 8: a) Average error velocity with depth for *Mphmed93*. b) Error velocity histogram for depths< 200 m.

FIGURE 1



FE92 cruise
Europe
Alboran Sea
Africa
a)
Latitude
Longitude
38
37
36
35
-5
-4
-3
-2
-1
Calibration leg
51
124
72
121
58
98
37
1
b)
Latitude
Longitude
36.4
36.3
36.2
36.1
36
-5.2
-5.1
-5
-4.9
-4.8

FIGURE 2

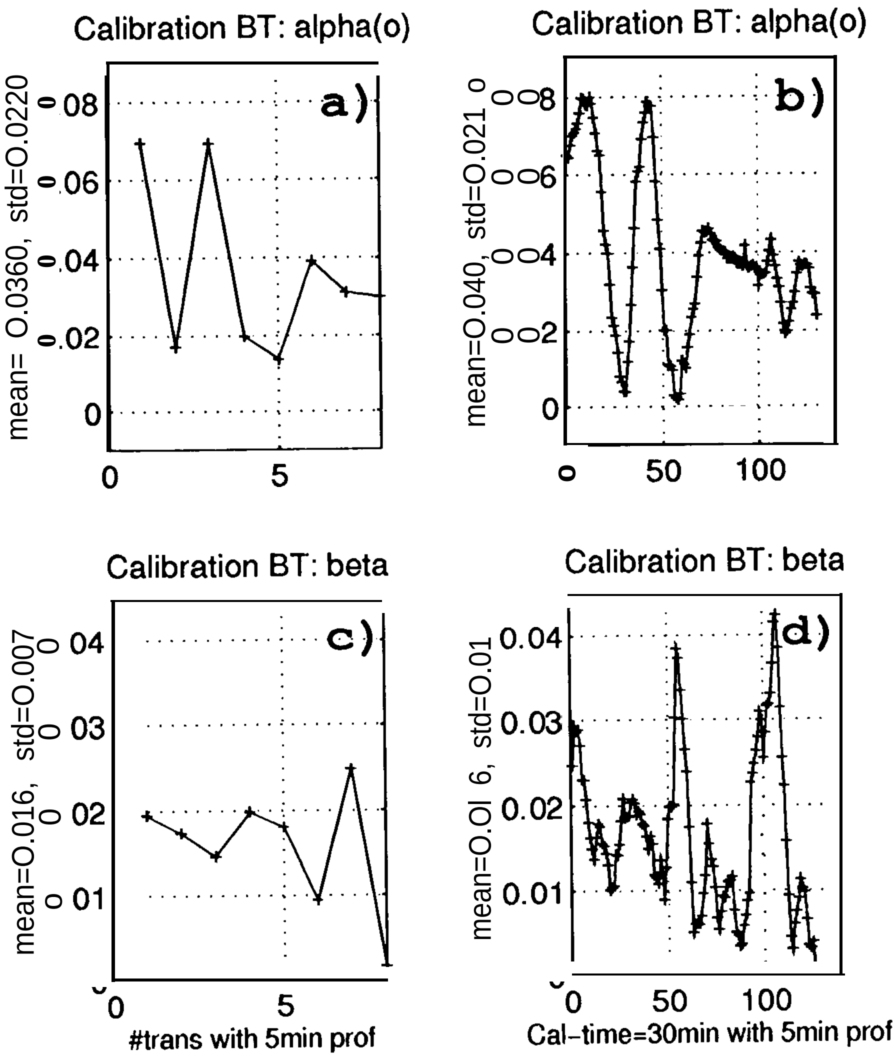
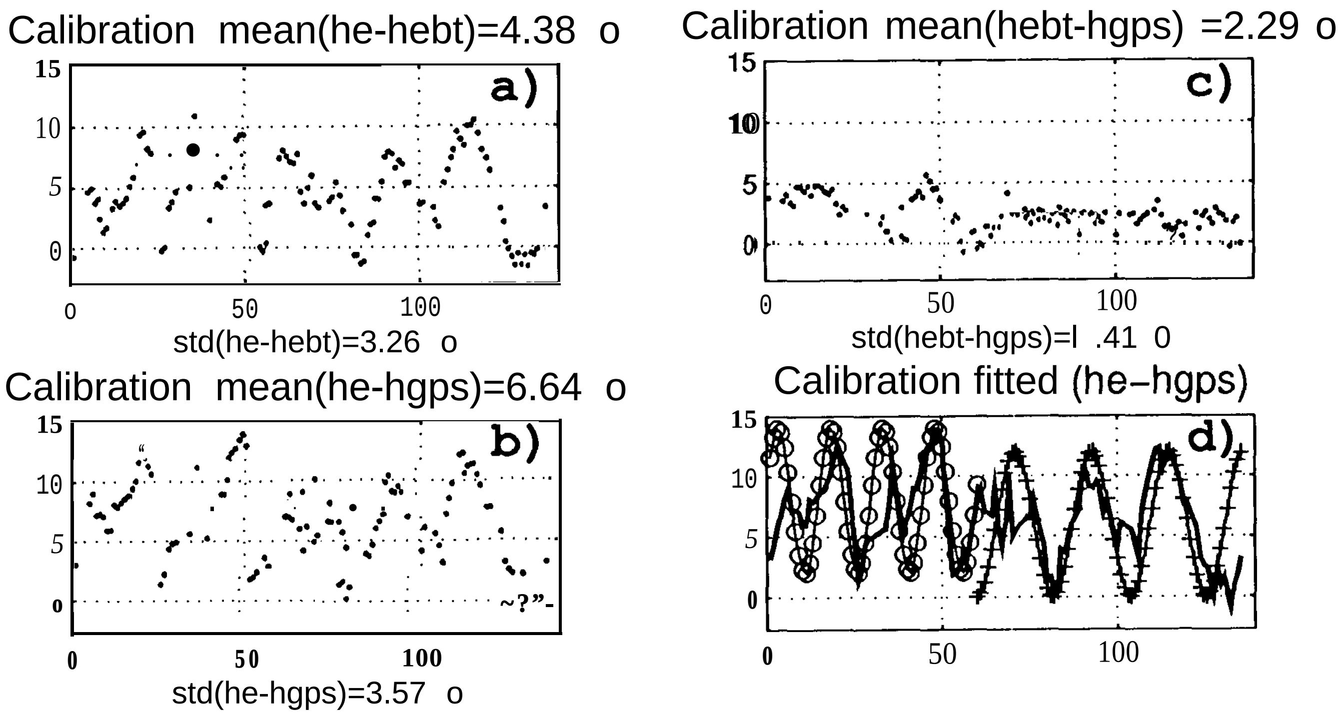
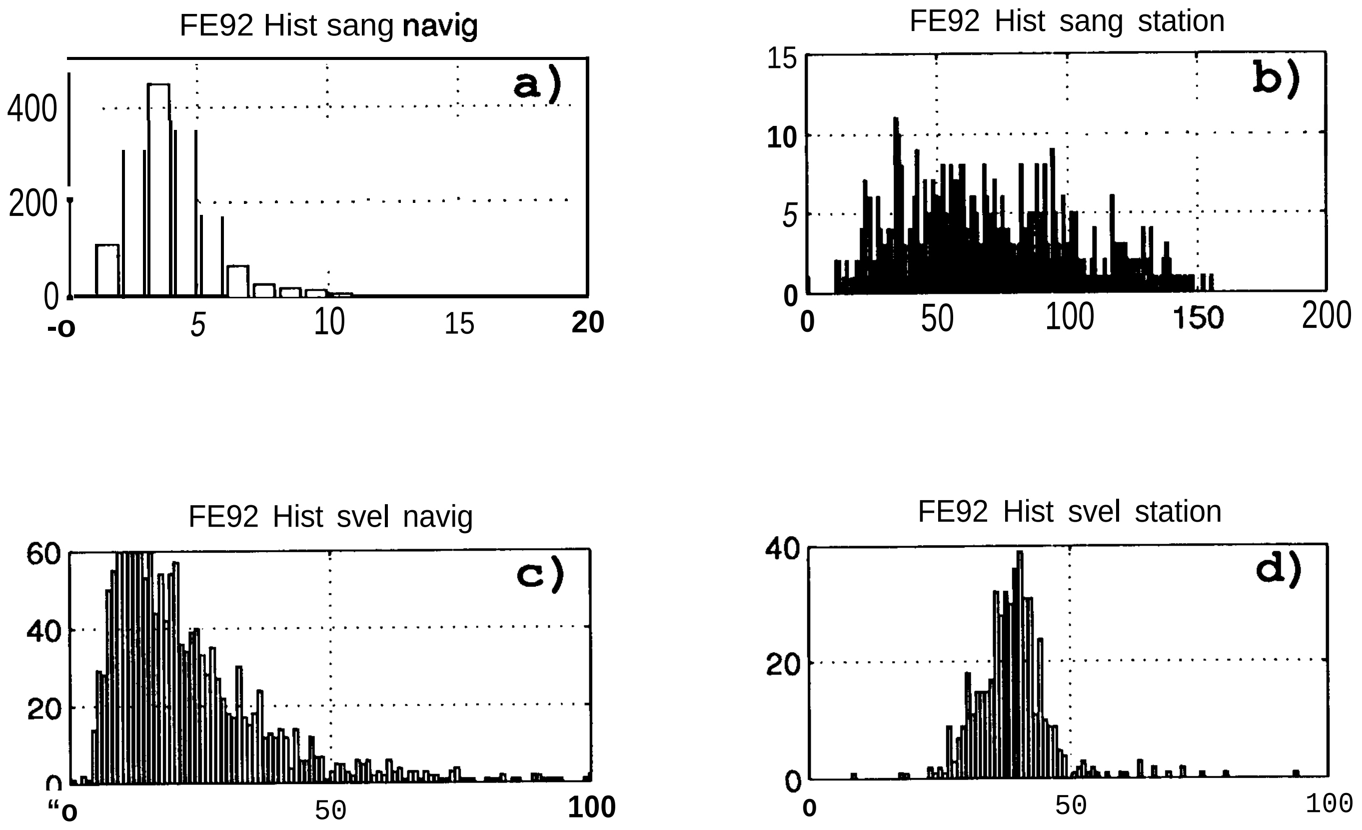

Calibration BT: alpha(o)
mean= O.0360, std=O.0220
a)
Calibration BT: alpha(o)
mean=O.040, std=O.021
b)
Calibration BT: beta
mean=O.016, std=O.007
c)
#trans with 5min prof
Calibration BT: beta
mean=O.Ol 6, std=O.01
d)
Cal-time=30min with 5min prof

FIGURE 3



Calibration mean(he-hebt)=4.38 o
a)
std(he-hebt)=3.26 o
Calibration mean(hebt-hgps) =2.29 o
c)
std(hebt-hgps)=l .41 0
Calibration mean(he-hgps)=6.64 o
b)
std(he-hgps)=3.57 o
Calibration fitted (he–hgps)
d)
15
10
5
0
0
50
100

FIGURE 4



FE92 Hist sang navig
a)
400
200
0
-o
5
10
15
20
FE92 Hist sang station
b)
15
10
5
0
0
50
100
150
200
FE92 Hist svel navig
c)
60
40
20
0
"o
50
100
FE92 Hist svel station
d)
40
20
0
0
50
100

FIGURE 5

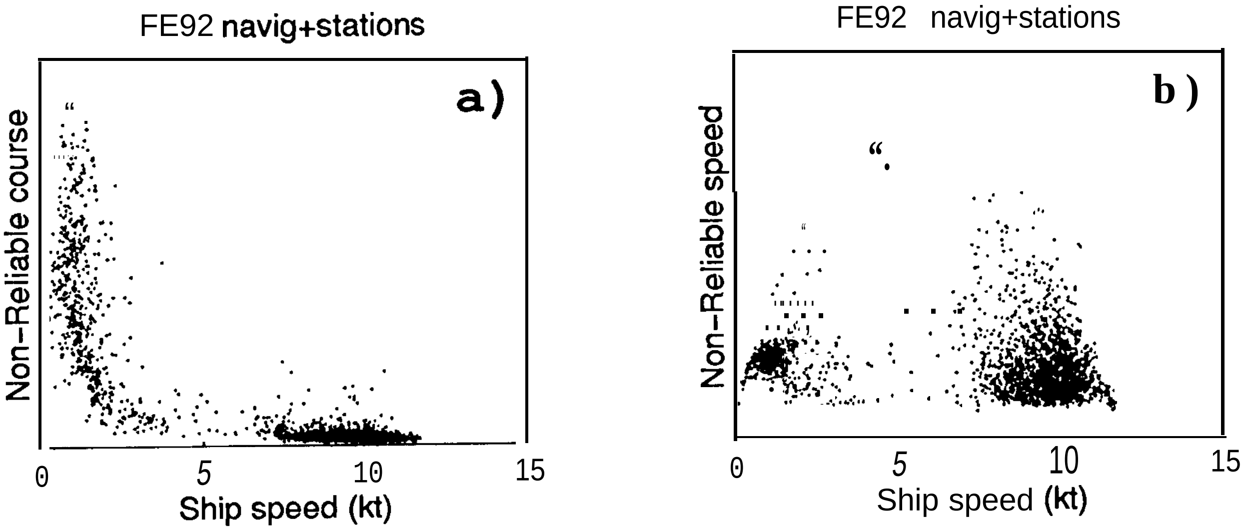
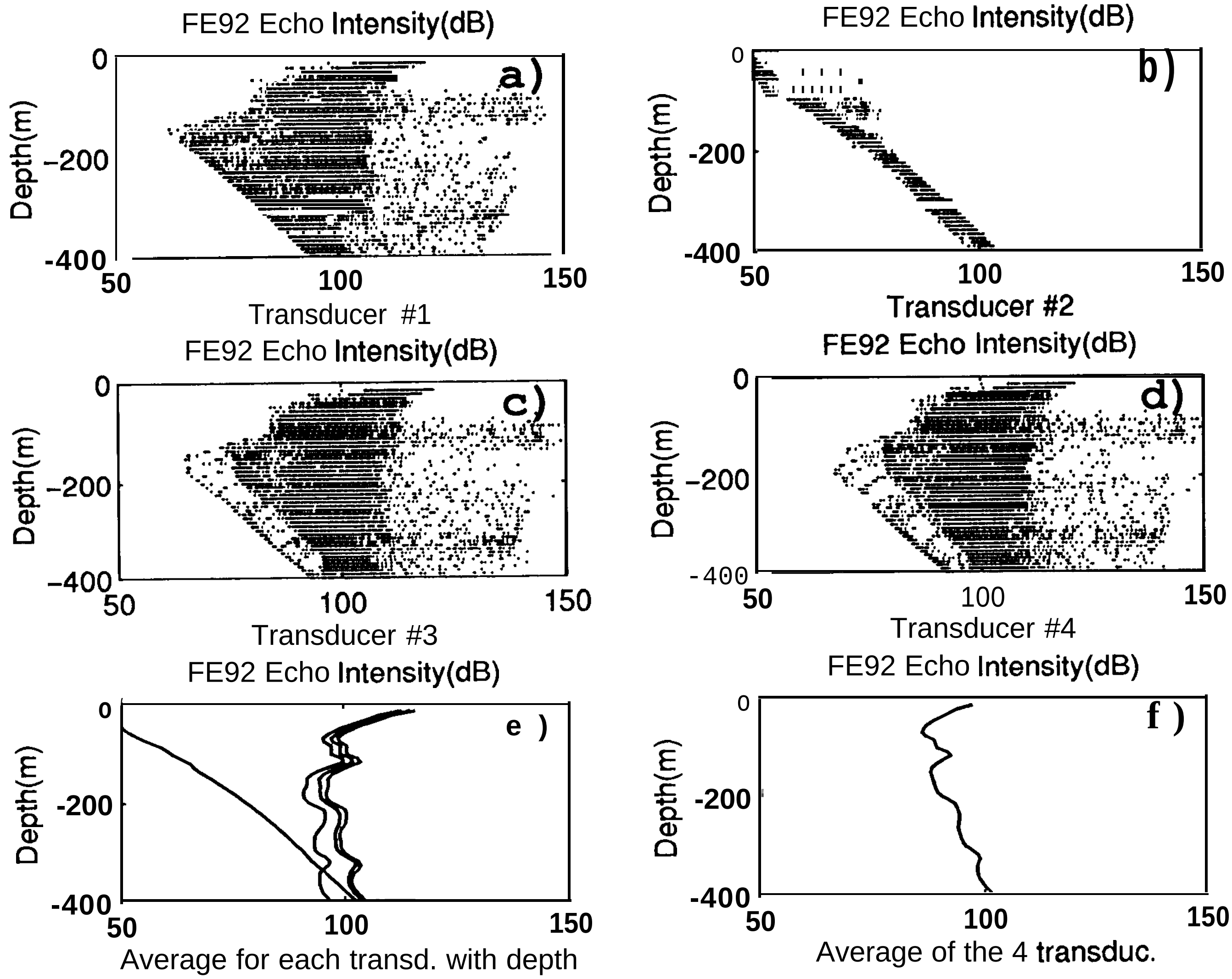
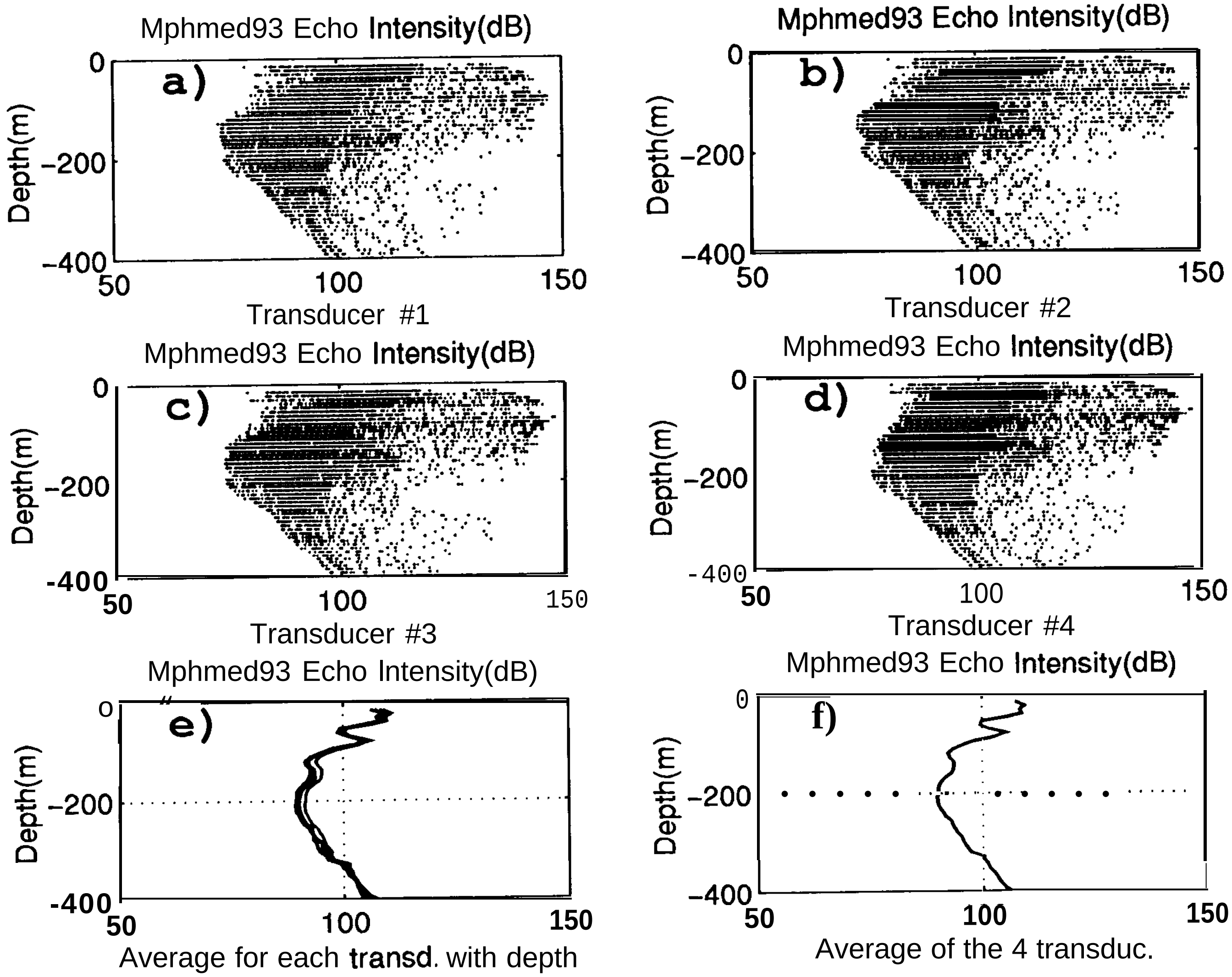

FE92 navig+stations
a)
Non-Reliable course
0
5
10
15
Ship speed (kt)
FE92 navig+stations
b)
Non-Reliable speed
0
5
10
15
Ship speed (kt)

FIGURE 6



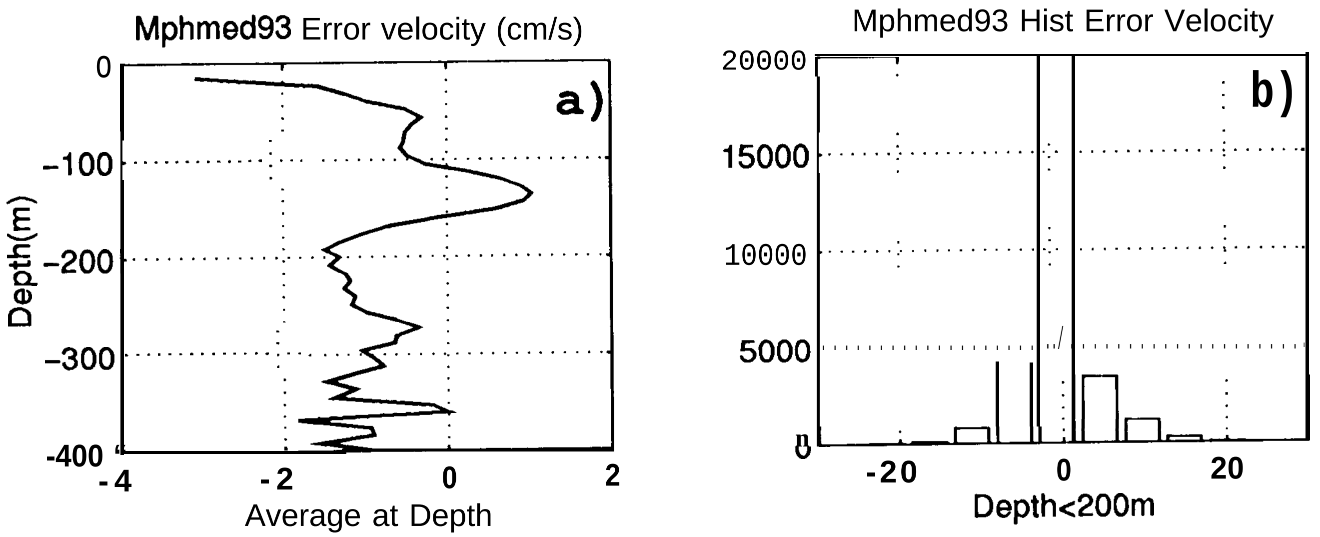
FE92 Echo Intensity(dB)
a)
Depth(m)
0
-200
-400
50
100
150
Transducer #1
FE92 Echo Intensity(dB)
b)
Depth(m)
0
-200
-400
50
100
150
Transducer #2
FE92 Echo Intensity(dB)
c)
Depth(m)
0
-200
-400
50
100
150
Transducer #3
FE92 Echo Intensity(dB)
d)
Depth(m)
0
-200
-400
50
100
150
Transducer #4
FE92 Echo Intensity(dB)
e)
Depth(m)
0
-200
-400
50
100
150
Average for each transd. with depth
FE92 Echo Intensity(dB)
f)
Depth(m)
0
-200
-400
50
100
150
Average of the 4 transduc.

FIGURE 7



Mphmed93 Echo Intensity(dB)
a)
Depth(m)
0
-200
-400
50
100
150
Transducer #1
Mphmed93 Echo Intensity(dB)
b)
Depth(m)
0
-200
-400
50
100
150
Transducer #2
Mphmed93 Echo Intensity(dB)
c)
Depth(m)
0
-200
-400
50
100
150
Transducer #3
Mphmed93 Echo Intensity(dB)
d)
Depth(m)
0
-200
-400
50
100
150
Transducer #4
Mphmed93 Echo Intensity(dB)
e)
Depth(m)
0
-200
-400
50
100
150
Average for each transd. with depth
Mphmed93 Echo Intensity(dB)
f)
Depth(m)
0
-200
-400
50
100
150
Average of the 4 transduc.

FIGURE 8



Mphmed93 Error velocity (cm/s)
a)
0
-100
-200
-300
-400
Depth(m)
-4
-2
0
2
Average at Depth
Mphmed93 Hist Error Velocity
b)
20000
15000
10000
5000
0
-20
0
20
Depth<200m